Motivation: what accuracy is required for various experiments

Methods in use:
- Optical methods
- Mott scattering
- Moller scattering
- Compton scattering

Most accurate polarimeters and ways to improve

Conclusion
Electron Beam Polarimetry: Status and Prospects

Demand for Electron Beam Polarimetry and Accuracy Required

Double Spin Experiments
- $\vec{e}^- \vec{N} \rightarrow e^- X$ DIS - PDF, GDH
- $\vec{e}^- \vec{N} \rightarrow e^- N$ elastic: formfactors
- $\vec{e}^- N \rightarrow e^- \vec{N}$ elastic: formfactors
- $\vec{e}^- \vec{e}^+ \rightarrow X$ SM

Single Spin Experiments
- Neutral currents - parity violation (PV)
  - $\vec{e}^- N \rightarrow e^- X$ DIS - SM tests
  - $\vec{e}^- p \rightarrow e^- p$ formfactors, SM
  - $\vec{e}^- A \rightarrow e^- A$ nuclear physics
  - $\vec{e}^- e^+ \rightarrow X$ SM
- Charged currents $\vec{e}^- p \rightarrow \nu X$ - SM

$A_{obs} \propto P_{beam} \times P_{target} \times A_{reaction}$

Typically $\frac{\sigma(P)}{P}_{target} > \frac{\sigma(P)}{P}_{beam}$

Required: $\frac{\sigma(P)}{P}_{beam} < 2 - 3\%$

Required: $\frac{\sigma(P)}{P}_{beam} < 1\%$
Challenges to Polarimetry at JLab

Parity violating electron scattering experiments:

- Progress in reducing the systematic errors
- Beam polarization: becomes the dominant error!

JLab planned experiments, beam current 50-100 μA:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Syst. err without pol</th>
<th>Polar. error</th>
<th>Stat. error</th>
<th>Energy GeV</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{208}Pb$ n-skin</td>
<td>0.5%</td>
<td>1.0%</td>
<td>3.0%</td>
<td>0.85</td>
<td>soon</td>
</tr>
<tr>
<td>eP $sin^2 \theta_W$</td>
<td>2.4%</td>
<td>&lt;1.4%</td>
<td>2.8%</td>
<td>1.16</td>
<td>soon</td>
</tr>
<tr>
<td>DIS $sin^2 \theta_W$</td>
<td>0.3%</td>
<td>&lt;1.0%</td>
<td>0.8%</td>
<td>10.0</td>
<td>after 12 GeV upgrade</td>
</tr>
</tbody>
</table>

A 1%, polarimetry accuracy is needed A 0.5% accuracy would be even better...
Important Features of Beam Polarimetry

- Energy range $E_{beam} = 0.5 - 50 \text{ GeV}$, in future ILC $E_{beam} > 250 \text{ GeV}$
- Low energy range $E_{beam} = 0.1 - 5 \text{ MeV}$ needed to test the injectors
- Current range $E_{beam} = 0.01 \mu \text{A} - 2 \text{ A}$, various duty cycles

- Systematic error
- Statistical error for a period of a possible polarization change
- Invasive or not
- Does polarimetry use the same beam (energy, current, location) as the experiment?
Methods Used for Absolute Electron Polarimetry

Spin-dependent processes with a known analyzing power.

**Atomic Absorption**

\[ \bar{e}^- \sim 50 \text{ keV} \text{ decelerated to } \sim 13 \text{ eV} \quad \bar{e}^-(13\text{eV}) + \text{Ar} \rightarrow \text{Ar}^* + e^- \quad \text{Ar}^* \rightarrow \text{Ar} + (h\nu)_\sigma \]

Atomic levels: \((3p^54p)^3D_3 \rightarrow (3p^64s)^3P_2\)

811.5nm fluorescence

Potential \(\sigma_{syst} \sim 1\%\). Under development (Mainz) - only relative so far.

Currently - invasive, diff. beam

**Spin-Orbital Interaction**

Mott scattering, 0.1-10 MeV: \(e^- + Z \rightarrow e^- + Z \quad \sigma_{syst} \sim 3\%\), \(\Rightarrow 1\% \) (?) invasive, diff. beam

**Spin-Spin Interaction**

- Møller scattering: \(\bar{e}^- + \bar{e}^- \rightarrow e^- + e^- \) at \(>0.1 \text{ GeV}\), \(\sigma_{syst} \sim 3-4\%\), \(\Rightarrow 0.5\%\)
  Mostly invasive, diff. beam

- Compton scattering: \(\bar{e}^- + (h\nu)_\sigma \rightarrow e^- + \gamma \) at \(>0.5 \text{ GeV}\), \(\sim 1-2\%\), \(\Rightarrow 0.5\%\).
  non-invasive, same beam
Electron Beam Polarimetry: Status and Prospects

**Mott Polarimetry**

0.1-10 MeV: \( e^- \uparrow + Au \rightarrow e^- + Au \) Analyzing power - Sherman functions \( \sim 1-3\% \):

- Nucleus thickness: phase shifts of scat. amplitudes
- Spin rotation functions
- Electron screening, rad. corrections
- Multiple and plural scattering
- No energy loss should be allowed
- Single arm - background

Extrapolation to zero target thickness

\( e^- \uparrow < 5 \mu A \) - extrapolation needed

**JLab:** \( \sigma(P) / P = 1\% (\text{Sherman}) \oplus 0.5\% (\text{other}) \) (unpublished) \( \oplus \sigma(\text{extrapol}) \)

DIS 2005, Madison, April 29, 2005

E.Chudakov (JLab)
Compton Polarimetry

\[ \vec{e}^- + (h\nu)_\sigma \rightarrow e^- + \gamma \quad \text{QED.} \]

- Rad. corrections to Born < 0.1%
- Detecting the \( \gamma \) at 0 angle
- Detecting the \( e^- \) with an energy loss
- Strong \( \frac{dA}{dk'} \) - good \( \sigma E_\gamma / E_\gamma \) needed
- \( A \propto kE \) at \( E < 20 \text{ GeV} \)
- \( T \propto 1/(\sigma \cdot A^2) \propto 1/k^2 \times 1/E^2 \)
- \( \mathcal{P}_{\text{laser}} \sim 100\% \)
- Non-invasive measurement

Syst. error 3→50 GeV: \( \sim 1. \rightarrow 0.5\% \)

Hard at \( < 1 \text{ GeV} \): (JLab project) \( \sim 0.8\% \)

Møller Polarimetry

\[ \vec{e}^- + \vec{e}^- \rightarrow e^- + e^- \quad \text{QED.} \]

- Rad. corrections to Born < 0.3%
- Detecting the \( e^- \) at \( \theta_{CM} \sim 90^\circ \)
- \( \frac{dA}{d\theta_{CM}} \bigg|_{90^\circ} \sim 0 \) - good systematics
- Beam energy independent
- Coincidence - no background
- Ferromagnetic target \( \mathcal{P}_T \sim 8\% \)
  - \( > 1 \mu\text{m} \): invasive measurement
  - Beam \( I_B < 2 - 4 \mu\text{A} \) (heating)
  - Levchuk effect
  - Low \( \mathcal{P}_T \Rightarrow \) dead time
  - Syst. error \( \sigma(\mathcal{P}_T) \sim 3\% \) (0.3%)

Syst. error \( \sim 3\% \) typically, (0.5%)
Electron Beam Polarimetry: Status and Prospects

Møller Polarimeter with Saturated Iron foil

JLab, Hall C, M. Hauger et al., NIM A 462, 382 (2001)

- External $B_Z \sim 4\ T$
- Target foils 4-10 $\mu$m, perp. to beam
- $P_t$ not measured
- Important: annealing, etc.

Tests for high current

- Beam $\sigma_X \sim 50\mu$m $> r = 12\mu$m
- At 20$\mu$A - accidentals/real$\approx 0.4$
- $\sigma_{stat} \sim 1\%$ in 2h

Current Studies

- A 1$\mu$A thick half-foil
- Higher duty factor

<table>
<thead>
<tr>
<th>source</th>
<th>$\sigma(A)/A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>optics, geometry</td>
<td>0.20%</td>
</tr>
<tr>
<td>target</td>
<td>0.28%</td>
</tr>
<tr>
<td>Levchuk effect</td>
<td>0.30%</td>
</tr>
<tr>
<td>total</td>
<td>0.46%</td>
</tr>
<tr>
<td>$\Rightarrow 100\ \mu$A</td>
<td>?</td>
</tr>
</tbody>
</table>
Møller Polarimeter with Atomic Hydrogen Target


Ultra-cold traps

Contamination and Depolarization at 100µA CEBAF

- Hydrogen molecules < 2 \cdot 10^{-5}
- Upper states |c⟩ and |d⟩ < 10^{-5}
- Excited states < 10^{-5}
- Helium, residual gas <0.1% - beam-measurable
- Depolarization by beam RF < 5 \cdot 10^{-5}
- Ion, electron contamination < 10^{-5}
- Ionization heating < 10^{-10}

Expected depolarization < 10^{-4}

Limitations

- Problems ∝ \mathcal{I}_b^2/\mathcal{F} ⇒ “continuous” beam (MAMI, CEBAF ...)
- Complexity of the target

Advantages

- Expected accuracy < 0.5%
- Non-invasive, continuous, the same beam

Atom \( H_1 \): \( \vec{\mu} \approx \vec{\mu}_e, \quad E = -\vec{\mu}\vec{B} \)

Population \( \propto \exp(-E/kT) \)

At 300 mK \( P_e \sim 1 - 10^{-5} \)

Density \( \sim 3 \cdot 10^{15} cm^{-3} \)

Lifetime > 1 h

Stat. 1% in 10 min at 100 µA
Electron Beam Polarimetry: Status and Prospects

**Bhabha/Møller Scattering at Colliders**

**Linear Collider**
- Depolarization in bunch collisions \(\Rightarrow\) measurement at the collision point!
- \(e^+e^- 250 \times 250\) GeV
  \(\mathcal{L} \sim 3 \cdot 10^{34}\) cm\(^{-2}\)
- Experiment \(1 \cdot 10^7\) s, \(\mathcal{L} \sim 3 \cdot 10^5\) pb\(^{-1}\)
- \(\frac{d\sigma}{d\Omega_{CM}}_{\text{Bhabha}} \sim 0.2\) pb/Ster
- \(\sim 10^5\) events \(\Rightarrow\) \(\sigma(\mathcal{P})/\mathcal{P} \sim 0.7\%\)
- \(W\) - production
- s-channel vector exchange - Blondel scheme

**Electron-Ion Collider - JLab Design**
- \(e^-e^- 3 \times 3\) GeV - 7 \times 7 GeV
  a new collision point at the center
- \(\mathcal{L} \sim 1 \cdot 10^{35}\) cm\(^{-2}\)
- \(\frac{d\sigma}{d\Omega_{CM}}_{\text{Møller}} \sim 1000\) pb/Ster
- Stat. 1% in 5 min
- A high luminosity collision point - some other interest?

Faster methods are needed (Compton)
Electron Beam Polarimetry: Status and Prospects

Compton Polarimeters: Best Accuracy at High Energy

SLAC SLD

Stat: 1% in 3 min

<table>
<thead>
<tr>
<th>Source</th>
<th>(\sigma(P)/P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLD 1998</td>
<td>0.10%</td>
</tr>
<tr>
<td>ILC Goal</td>
<td>0.10%</td>
</tr>
<tr>
<td>Laser polarization</td>
<td>0.10%</td>
</tr>
<tr>
<td>Analyzing power</td>
<td>0.40%</td>
</tr>
<tr>
<td>Linearity</td>
<td>0.20%</td>
</tr>
<tr>
<td>Electronic noise</td>
<td>0.20%</td>
</tr>
<tr>
<td>Total</td>
<td>0.50%</td>
</tr>
<tr>
<td>Goal</td>
<td>0.25%</td>
</tr>
</tbody>
</table>

M.Woods, JLab Polarimetry workshop, 2003

- Beam: 45.6 GeV
- Beam: \(3.5 \cdot 10^{10} e^- \times 120 \text{ Hz} \sim 0.7 \mu A\)
- Laser: 532 nm, 50 mJ at 7 ns \times 17 Hz
- Crossing angle 10 mrad
- \(e^-\) 17-30 GeV detector - gas Cherenkov
- \(\gamma\) detector - calorimeter
Electron Beam Polarimetry: Status and Prospects

Compton Polarimeters: CW Low Energy Beam - Cavity

Electron Beam

Electrons detector

Magnetic Chicane

Photons detector

\( \lambda = 1064 \text{ nm, } k = 1.65 \text{ eV} \)

Source \( P = 1 \text{kW} \)

Upgrade Plans - 1% at 0.85 GeV

- Laser: 532 nm, 0.1 W
- Cavity \( \times 15000 \Rightarrow 1.5 \text{ kW} \)
- Detector upgrade

JLab Hall A Compton

- Beam: 1.5-6 GeV
- Beam: 5 – 100 \( \mu \text{A} \) at 500 MHz
- Laser: 1064 nm, 0.24 W
- Fabry-Pérot cavity \( \times 4000 \Rightarrow 1 \text{ kW} \)
- Crossing angle 23 mrad
- \( e^- \) detector - Silicon \( \mu \)-strip
- \( \gamma \) detector - calorimeter

Stat: 1.0% in 30 min at 4.5 GeV, 40 \( \mu \text{A} \)

Syst: 1.2% at 4.5 GeV

<table>
<thead>
<tr>
<th>Source</th>
<th>( \sigma(P)/P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser polarization</td>
<td>0.50%</td>
</tr>
<tr>
<td>Response function</td>
<td>0.40%</td>
</tr>
<tr>
<td>Calibration</td>
<td>0.60%</td>
</tr>
<tr>
<td>Others</td>
<td>0.65%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.15%</strong></td>
</tr>
</tbody>
</table>
Electron Beam Polarimetry: Status and Prospects

Compton Polarimeters: Storage Rings (DESY)

The LPOL

Current
- $\sim 30 \text{ GeV } 3 \cdot 10^{10} e^- \times 10 \text{ MHz } \sim 40 \text{ mA}$
- Laser: 532 nm, 100 mJ at $<100 \text{ Hz}$
- Crossing angle 8.7 mrad
- $\gamma$ detector - calorimeter

Stat: 1.0% in 2 min in multi-photon mode
Syst: 1.6%

New Polarimeter
- Cavity 1064 nm (as JLab)
- Single bunch measurement
- Expected systematics: $\sim 0.1\%$
Electron Beam Polarimetry: Status and Prospects

Compton Polarimeters: Storage Rings (DESY)

- Transverse polarization
- Laser: 532 nm CW
- Crossing angle 3.1 mrad
- Single photon mode
- \( \gamma \) detector - calorimeter
  
  Syst: 1.9%

TPOL

TPOL vs LPOL

- Stable for HERA-I
- Difference <2%

Stable for HERA-I²

Crossing angle

²

Laser:

²

Syst:

nan

DIS 2005, Madison, April 29, 2005
E.Chudakov (JLab)
Conclusion

- Accuracy of \( \sim 1.0\% \) becomes common for Compton polarimetry
- Accuracy of \( \sim 0.5\% \) is still exceptional
- Compton polarimetry fits very well the high energy storage rings
- Moller polarimetry can be used at low energy, one may be able to reach \( < 0.5\% \)